Comparative Embodied Energy Analysis of a Steel and Concrete Structural System in Ireland

Adolf Acquaye
Technological University Dublin, adolf.acquaye@tudublin.ie

Aidan Duffy
Technological University Dublin, aidan.duffy@tudublin.ie

Biswajit Basu
Trinity College

Recommended Citation

Acquaye, A., Duffy, A. & Basu, B. (2007). Comparative embodied energy analysis of steel and concrete structural systems in Ireland.Proceedings of SECOTOX Conference and the International Conference on Environmental Management, Engineering, Planning and Economics(eds. A. Knugolos, K. Aravossis, A. Karagiannidis, P. Samaras). *Proceedings of the First Conference on Environmental Management, Engineering, Planning and Economics (CEMPE)* Skiathos, Greece, 24-28 June, pp.347-353.

2007-01-01

Comparative Embodied Energy Analysis of a Steel and Concrete Structural System in Ireland

Adolf Acquaye
Dublin Institute of Technology, adolf.acquaye@dit.i

Aidan Duffy
Dublin Institute of Technology, aidan.duffy@dit.ie

Biswajit Basu
Trinity College Dublin

Proceedings of SECOTOX Conference and the International Conference on Environmental Management, Engineering, Planning and Economics

Volume I

Organized by:

Department of Planning and Regional Development, School of Engineering
University of Thessaly

In collaboration with:

Technical Chamber of Greece (TCG),
Department of Mechanical Engineering, Aristotle University of Thessaloniki,
Sector of Industrial Management and Operations Research, School of Mechanical Engineering, National Technical University of Athens,
Department of Pollution Control Technologies, Technological Educational Institute of West Macedonia,
Hellenic Association of Mechanical and Electrical Engineers (HAMEE),
Hellenic Association of Chemical Engineers (HACE),
International Society of Ecotoxicology and Environmental Safety (SECOTOX)

Under the aegis of:

Hellenic Ministry for Environment, Physical Planning and Public Works

EDITORS: A. Kungolos
K. Aravossis
A. Karagiannidis
P. Samaras

pollution that anyhow is at acceptable levels. The aesthetic values of the lake indicated acceptable levels and a place suitable for recreational activities. The use of the corresponding PSIR indicators is indicative and proved useful for the data considered. These indicators are also a tool, which was used for reference in terms of comparison with previous researchers about the nature and behaviour of the river at the monitoring points. The information obtained from this research program constitutes the first document describing the state of the Polyfyto Lake over a period of twelve months at three monitoring stations in Kozani West Macedonia Greece. In the future it will enable correct decisions to be made about the activities of the many communities living in areas, which influence the Aliakmon River.

Acknowledgement
This study is a by-product of the EPEAEK II project "2.6.1.ιβ. Environment-Archimedes, A Support of Research in issues of Environment and Ecology in Technological Education Institutes" financed 75% by E.C and 25% by Greek government.

References

1. Dimitrakopoulos, D., Koumantakis, I. & Iliadis, Z., 1996. Development of an integrated water resources management system and methods of artificial enrichment in open pit areas of lignite mines. The case of Southern Field Mining Area of Ptolemais basin. *International Conference of Technical Chamber of Greece,* Dep. of Central and Western Thessalia, Larissa.
2. ELIMEIA project, 1999. Development of water resources management system, and methods for the enrichment, in open pit minings. *Pilot study in south field of coal basin area.* Kozani, Greece. Final report in Greek, NTUA publication, May 1999. Athens, Greece.
3. Sachanidis, C., Laskos, K., 2000. Water quality of lignite mines in Ptolemais – Amynteon basin. Problems, Remediation and Relationships to the Environment. *Proceedings of the 1st Conference of the Committee of Economic Geology, Mineralogy and Geochemistry.* Mineral Wealth and Environment of W. Macedonia, Feb., 2000, Kozani, 380-397.
4. Panilas, S., Koumantakis, I., 2001. Groundwater qualitative characteristics of the Southern part of Ptolemais basin. *Proceedings of 9th International Conference,* Athens, 1893-1901.
5. Ferrier, R.C., Edwards, A.C., 2002. Sustainability of Scottish water quality in the early 21st century. *The science of total Environment,* **294,** 57-71.
6. OECD, Organization for Economic Cooperation and Development, 1998. *Towards Sustainable Development- Environmental Indicators.* OECD Paris.
7. Eurostat, 1999. *Towards Environmental Pressure Indicators for the EU.* European Communities, Luxemburg.
8. United Nations, 1996. *Indicators for Sustainable Development framework and methodologies.* United Nations, New York.
9. Voutsa, D., Zachariadis, G., Samara C., Kouimtzis, Th., 1995. Evaluation of Chemical parameters in Aliakmon river/Northern Greece. *Journal Environmental Science Health,* **A30 (1)**, 1-13.
10. Kouimtzis, Th., Samara, C., Voutsa, D., Zachariadis, G., 1994. Evaluation of Chemical parameters in Aliakmon river, Northern Greece. *Journal Environmental Science Health,* **A29 (10)**, 2115-2126.
11. KYA 46399/4352/1986 (Gov. Gaz. 438B/3-7-1986) «Quality of surface waters indented for potable, quality of bathing waters, quality of fresh water to support fish life, quality of shellfish waters, methods of measurement, sampling frequency and analysis of surface waters intended for potable» according to EU Directives 75/440, 76/160, 78/659, 79/923 and 79/869.

Comparative embodied energy analysis of a steel and concrete structural system in Ireland

A. A. Acquaye[1,2] *, A. P. Duffy[1,2] and B. Basu[3]
[1]Dublin Energy Lab, Focas Institute, Camden Row, Dublin 8, Ireland
[2]Civil Engineering Department, Dublin Institute of Technology, Bolton Street, Dublin 1, Ireland
[3]Department of Civil, Structural & Environmental Engineering, Trinity College Dublin 2, Ireland

*Corresponding author: Email: adolf.acquaye@student.dit.ie, Telephone: 00353-851706231

Abstract
Engineering building design focuses on optimising operational energy use and ignores the energy required to procure and construct a building. This energy, termed 'embodied energy', can be very significant when compared to operational energy. Therefore, it is important to minimise the embodied in buildings; this must be done at the design stage. This paper presents a comparative embodied energy analysis of two structural design solutions for a modern office building: one in concrete and one in steel. Process analysis is used to determine production, transport and construction energy requirements for all system components. Results indicate that the steel solution has more than two and a half times as much embodied energy as the concrete solution.
Keywords: embodied energy; structural steel and concrete-framed buildings; Ireland.

1. INTRODUCTION

Embodied energy is the total energy consumed by all the processes associated with the production of a product. For a building material, embodied energy represents the energy used in the extraction of materials, their processing, manufacture, and transportation. It also includes further upstream energy inputs such as energy associated with capital equipment and services.

Many researchers have worked on embodied energy and life cycle assessment methodologies to assess the embodied energies of materials and products [1, 2, and 3]. However, this study focuses on analysing the comparative embodied energies of two equivalent structural solutions for a modern commercial building: one in concrete and one in steel.

When choosing a structural system for a building, many factors must be considered. For example: procurement periods, local construction expertise, appearance and aesthetics, operational energy efficiency and, most importantly, cost. Whereas considerable design effort is expended in minimising operational energy use in Ireland, no consideration is given to minimising the embodied energy in a building; this situation is likely to pertain internationally. However it has been calculated that the total embodied energy of a building could be as high as 67% of the operational energy use of a building over a 25 year period [4]. The embodied energy of buildings is currently a particularly important issue in Ireland, where the construction sector accounted for 19.6% of Gross Domestic Product (GDP) in 2005 [5]. This is high by international standards.

Structural steel- and concrete-framed buildings are two of the most widely used options for Irish commercial buildings. Because the steel and cement industries are also two of the most energy intensive manufacturing industries in the world [6], the embodied energy of these structural options should therefore be of particular interest to designers due to their impact on the global environment.

Proceedings of the International Conference on Environmental Management, Engineering, Planning and Economics Editors: *A. Kungolos, K. Aravossis, A. Karagiannidis, P. Samaras*
Skiathos, June 24-28, 2007, Pages: 347-353

The foregoing illustrates the importance of embodied energy in the Irish building sector and the relatively high embodied energy associated with these materials. Therefore the aim of this paper is to undertake a comparative analysis of steel and concrete structural solutions for a generic commercial building in Ireland and to calculate the respective embodied energies for both.

2. STRUCTURAL OPTIONS

The generic open plan commercial building adopted in the embodied energy analysis is a 48m long and 13.5m wide rectangular four storey building [7]. The total floor area of the building is $2592m^2$. This building design was chosen for the study because it represents a commonly used commercial building. Two structural solutions are considered due to their prevalence in the Irish construction sector. These are: composite steel and composite slab; and reinforced concrete flat slab. These are referred to henceforth as the 'steel option' and the 'concrete option' respectively.

The steel option comprises a steel frame with profiled metal deck onto which a reinforced concrete slab is poured. The slabs are 130mm deep and are supported by a 60mm trapezoidal shaped decking. A mesh is used to reinforce the concrete slabs. The thickness of steel decking used is 0.9mm (See Figure 1 below).

The concrete option involves a steel-reinforced, cast *in situ* concrete structure. The percentage reinforcement is 1% of the cross-section of the slab with a slab depth of 300mm. (See Figure 2 below).

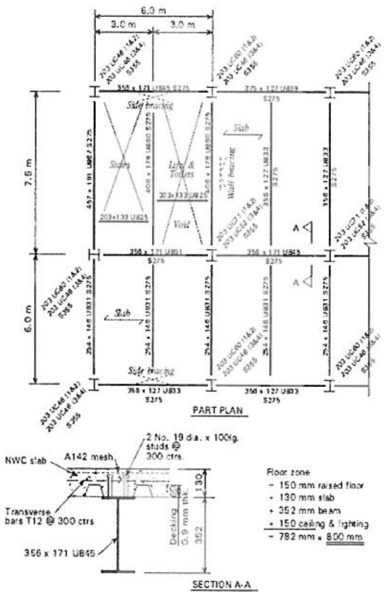

Figure 1. Composite beams and composite slab; 'steel option' (Adopted from: SCI, 2004).

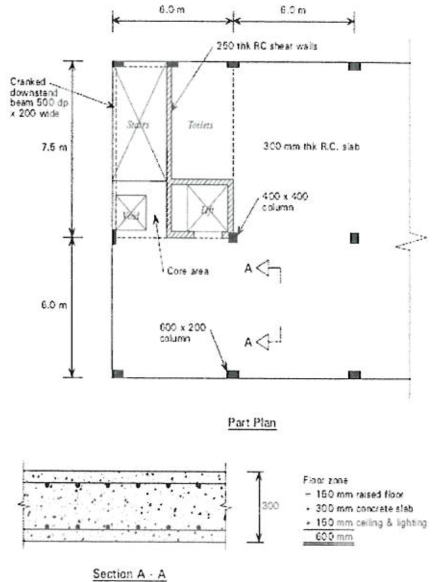

Figure 2. Reinforced concrete flat slab; 'concrete option' (Adopted from: SCI, 2004).

3. EMBODIED ENERGY ANALYSIS MODEL

The embodied energies for the steel and concrete options considered in this study are based on the energy used in material production, transportation and in their eventual construction on site.
Embodied Energy, $E_e = E_p + E_t + E_c$

E_p = Energy due to production of the material
E_t = Energy due to transportation
E_c = Energy due to construction

3.1 Steel Production Energy

The main processes in primary steel-making are: mining of raw materials, carbonisation of blended coal to produce coke, extraction of iron from iron ore in a reduction process, processing of molten iron to produce steel, casting, rolling and shaping. The reduction of iron ore is the most energy intensive stage of the steel-making process. However, not all steel has the same embodied energy. The energy intensity of steel production in some developing countries such as China is higher than in many industrialised nations such as the United States and Japan [6]. Variation in energy intensity values by country is due to technology used [6] and indigenous resource endowment and energy prices [8].

Since the closure of Irish ISPAT, formally Irish Steel in 2001, there is no production of steel in Ireland, and therefore all steel used is imported from steel producing countries. It is therefore more relevant to use energy intensity data from these countries. In this study it is assumed that the energy used for fabrication of steel in Ireland is negligible when compared to the total embodied energy due to production. For example, the energy used in cutting and welding in the fabrication shop is ignored. Embodied energy associated with timber shuttering is also ignored since this is insignificant compared to the total embodied energy of the reinforced concrete itself.

Assuming a waste factor of 5% for steel during production of structural fixtures [9], the embodied energy due to production of steel is given as;

$$E_p = 1.05QA\sum_{i=1}^{n} k_i e_i \tag{1}$$

Q= total quantity of concrete/steel used [kg]
A= Total floor area of the building [m^2]
k_i = ratio of steel imported from country/region i, to the total steel imported to Ireland
e_i= energy intensity of steel production in country i [MJ/kg]
n= total number of countries exporting steel to Ireland

3.2 Concrete Production Energy:

Cement, sand, aggregate and water are the main materials used in the manufacture of concrete. Because of the wide variety of cement, aggregate and sand types there are significant variations in the embodied energy of concrete. The cement type considered in this study is Ordinary Portland Cement (OPC) because it has about 80% usage in the construction industry in Ireland although Green cement; a more environmentally friendly cement is not widely used. Assuming a waste factor of 2.5% for concrete [9], the energy embodied in concrete production is given by;

$$E_p\ (\text{concrete}) = 1.025eQA \tag{2}$$

e= the energy intensity of concrete production in Ireland [MJ/kg]

3.2 Energy used in transport

The embodied energy due to road transportation of concrete in Ireland is given by;

$$E_t\ (\text{concrete}) = d_t r \tag{3}$$

The energy embodied due to the transportation of steel is given by;

$$E_t\ (\text{steel}) = 1.05QA\sum_{i=1}^{n} k_i D_i + d_2 r \qquad (4)$$

d_1= average distance from concrete plant to building site [km]
d_2= average distance from port in Dublin to the building site [km]
r = the energy intensity of road truck transport in Ireland [MJ/km]
D_i = Average nautical distance from country i to the port in Dublin, Ireland [km]
t_i = Energy intensity of the mode of transportation from country i to Ireland, [MJ/kg.km]

4. EMBODIED ENERGY CALCULATIONS AND RESULTS

4.1 Embodied Energy due to production, E_p

The weighted energy intensities of the various regions exporting steel to the European Union-15 (EU-15) region of which Ireland is a member is used in the calculations in order to give a true overall representative of steel use in EU-15. The energy intensities are calculated from data sourced from [6] and by combining data from [10 and 11]. This data was then combined with the 2004 World Steel in Figures Report published by the International Iron and Steel Institute [12] which summarises steel trade between regions and forms the basis for determining the likely origins of construction steel used in Ireland and consequently its embodied energy.

The energy intensities and percentage breakdown of steel exports into EU-15 by different countries/regions is represented in Table 1

Table 1.

Country/Region	Europe & EU-15	Fmr. USSR	N-America	L-America	Afr. & M.E	China	Japan	Other Asia
Percentage	87%	7%	0.3%	1%	2%	1%	0.3%	1%
Energy Intensity [GJ/ton]	17.5	21.9	21	23.1	44.4	36.7	17.5	18.4

4.1.1 Calculation of the embodied energy due to production E_p: Steel Option

The concrete considered in this study is Reinforced Cement Concrete, RCC with mix 1:1.5:3; 1 cement: 1.5 coarse sand: 3 graded stone aggregate 20mm nominal size respectively. This was taken to represent a typical mix for *in-situ* concrete works and commonly used to produce floor slabs, columns and load bearing structures. Because of the similarity in the production and construction industry in the UK and Ireland, an embodied energy value of 1.10 MJ/kg was chosen; this is representative of UK concrete [13]. From the structural drawing in Figure 1, the amount of concrete and steel used was calculated to be 260.8 and 43.7 [kg/m^2]. Applying Equations 1 and 2, E_p is calculated to be 2,981.5 GJ

4.1.2 Calculation of embodied energy due to production, E_p: Concrete Option

The total quantity of concrete and steel calculated from Figure 2 was found to be 248.2 and 8.2 kg/m^2 respectively based on a concrete density of 2,400kg/m^3, steel density of 7,850kg/m^3 and reinforcement equivalent to 1% of the cross-sectional area of slabs. Applying Equations 1 and 2, E_p is calculated to be 1,141.8GJ.

4.2 Calculation of embodied energy due to transportation, E_t

Data used for sea transportation was sourced from the Building Research Establishment-UK since it is assumed that the energy intensity of sea transport is similar in both the United Kingdom and in

Ireland. The energy consumption of sea transport is taken to be 0.0038 kg diesel/tonne-km [14] which is equivalent to 170J/kg-km, based on a diesel calorific value of 38MJ/litre and a density of 850kg/m^3.The nautical distances used are those from the largest producing steel exporters in the region to Dublin Port. A weighted average nautical distance of 1457.4 km is obtained.

A typical truck used for material delivery in Ireland is the Mercedes Axor, which has an average fuel consumption of 8.30 miles per gallon [15]. The average energy intensity of road transport is therefore taken to be 12.93MJ/km based on a on a diesel calorific value of 38MJ/litre. An average distance of 6.4km is assumed for the road transport of steel to and from Dublin Port to the site in Dublin City.

4.2.1 Calculation of embodied energy due to transport, E_t: Steel Option

Applying Equation 4, the energy due to transport of steel by sea and road is 29.5GJ. Assuming an average distance of 4km for road transport of concrete to and from the plant in Dublin, the road energy intensity is calculated to be equal to 51.7 MJ. The total embodied energy due to transport of steel is 29.6 GJ for the steel option.

4.2.2 Calculation of embodied energy due to transportation, E_t: Concrete Option

Similarly, applying Equation 4, the energy due to transport of steel by sea and road is 5.6 GJ. With a road intensity of 51.7MJ, the total embodied energy due to transport for the concrete option is 5.7GJ.

4.3 Calculation of embodied energy due to construction, E_c

Statistical data on construction from the Department of Trade and Industry, UK is combined with Irish energy production and carbon intensity data obtained from Sustainable Energy Ireland to calculate the embodied energy due to construction. Energy use in construction process is sourced from the UK because of the similarity in the construction industry in the two countries and the lack of equivalent Irish data. Estimated cost of the structural solutions is incorporated in the calculations. Using an Irish carbon intensity of 0.774kg CO_2/kWh [16]; construction process energy intensity of 209kg CO_2/€100K of project value [17] and cost of €99.4/ m^2 and €118/ m^2 for the steel and concrete options respectively [7], the embodied energies due to construction for the steel and concrete options are calculated to be equal to 2.5GJ and 3GJ respectively.

4.4 Results

Production, transportation, construction and total embodied energies for both the steel and concrete options are shown in Figure 3.

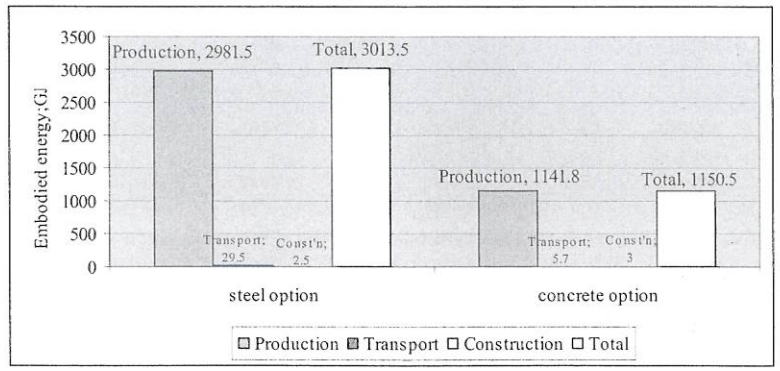

Figure 1.

5. DISCUSSIONS AND CONCLUSIONS

From Figure 3 it can be seen that the embodied energy of the steel option is over two and a half times greater than that of the concrete option. It can also be seen that production accounts for almost all (approximately 99%) of the embodied energies for both structural solutions. The energy used to transport the steel option is 80% greater than that of the concrete option. This due to the fact that steel is transported from steel producing countries all over the world whereas concrete is produced locally. The steel option was found to have 1,863GJ more embodied energy than to the concrete option. This is equivalent to approximately 325 tonnes of CO_2. Assuming an EU Emission Trading Scheme (ETS) price of carbon to be €5-10 per ton of CO_2 [18], the additional national cost of carbon for the building is estimated at €1,625-3,250. When it is considered that approximately 6 million square metres of non-residential buildings were constructed in Ireland in 2006/7, significant CO_2 emissions savings could be realised by switching from steel to concrete. For example, assuming all such buildings were structurally similar and constructed from steel, a switch to a concrete design would reduce annual CO_2 emissions by approximately 750,000 tonnes (Ireland is currently 7,000,000 tonnes over its agreed Kyoto target).

It is clear that the choice of structural option has a significant impact on embodied energy and CO_2 emissions. When considered at a national level, there is a significant potential for good building design and construction to help Ireland and other countries to meet their international emissions commitments.

References

1. Bullard, C.W., Penner, P.S., Pilati, D.A., 1978. Net energy analysis: a handbook for combining process and input-output analysis. *Resources and Energy*, **1**, 267–313
2. Bekker, P.C.F., 1982. A life-cycle approach in building. *Building and Environment*, **17 (1)**, 55-61.
3. Treloar, G.J., 1997. Extracting embodied energy paths from input-output tables: an input-output-based hybrid energy analysis method. *Economic Systems Research*, **9 (4)**, 375–91.
4. Yohanis, Y.G., Norton, B., 2002. Life-cycle operational and embodied energy for a generic single-storey office building in the UK *Energy*, **27**, 77–92.
5. AMA Research, 2005. Distribution of building & home improvement products - Republic of Ireland; Available at; http://www.amaresearch.co.uk/Ireland2005s.htm; (Assessed: 9 Jan 2007).
6. Price, L., Sinton, J., Worrell, E., Phylipsen, D., Hu, X., Li, J., 2002. Energy use and carbon dioxide emissions from steel production in China. *Energy* **27**, 429–446.
7. Steel and Construction Institute, SCI, 2004. Comparative structure cost of modern commercial building, 2nd Edition, Published: Steel & Construction Institute, Berkshire, UK.
8. United Nations, 2001. *Energy Efficiency, Promotion of energy efficiency in industry and financing of investments.* United Nations Publications; ISBN: 92-1-120035-0.
9. Chen, T.Y., Burnett, J., Chau, C.K., 2001.Analysis of embodied energy use in the residential building of Hong Kong. *Energy* **26**, 323–340.
10. United Nations Development Programme, 2000. *World Energy Assessment; Energy and the challenge of sustainability.* UNDP Bureau for Development Policy, NY; ISBN: 92-1-126126-0.
11. Yamaguchi, M., 2005. Factors that affect innovation, deployment and diffusion of energy-efficient technologies. *Workshop on Mitigation at SBSTA22*, Teikyo University, Japan.
12. International Iron and Steel Institute, IISI, 2006. *World Steel in figures*, IISI Statistical Publications; Brussels, Belgium.
13. Hammond, G., Jones, C., 2006. Inventory of Carbon and Energy; Version 1.5 Beta; University of Bath, United Kingdom.

14. Building Research Establishment, BRE, 1999. *BRE methodology for environmental profiles of construction materials, components and buildings.* Construction Research Communications Ltd Publishers; ISBN: 1 86081 294 5.
15. Transport News Network, 2006. Euro 5 on the road. Road Way magazine.
16. Sustainable Energy Ireland, SEI, 2005. *Fuel use and distribution in Ireland*, LIEN-Reporting energy and CO_2 emissions for carbon tax and emission trading.
17. Department of Trade and Industry, DTI, 2006. Construction Statistics Annual; London TSO.
18. Department of Trade and Industry, DTI, 2006. Carbon Prices; A Climate Change Projects Office (CCPO) guide, United Kingdom.